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# ENGAGING SELF-POWERED ENVIRONMENTAL SENSORS VIA SERIOUS GAMING

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**Abstract.** The monitoring of the Urban Environment requires the placement of many sensors around the City. Regular replacement of batteries is a significant additional cost. Can we enlist the public to keep the sensors charged, while keeping it entertained and engaged? The gamification of energy generation aims at inviting members of the public to interact with the energy generating device (EGD) to ensure that environmental sensors are constantly powered. As a collateral benefit, the physical and emotional involvement of the public with the EGD and the game are expected to raise their awareness and acceptance of environmental monitoring. Here we introduce the development of a hand-powered EGD and its installation on Newcastle University Campus.

## 1 Introduction

The locution “energy scavenging” was coined a few decades ago to indicate the generation of small electrical energy starting from some other form of energy present in the environment: vibrations, heat, radiation, etc. The initial purpose was simply the powering of small wireless sensors (a.k.a. motes) without recurring to batteries [1]. The term *energy harvesting* (EH) has recently been extended to include large scale generation from alternative sources or the tapping of energy which is not entirely free, but may require modest amounts of primary energy. Examples are radiation-based harvesters incorporating small radioactive sources [2] and most forms of wearable EH, where muscular work, often from a deliberate action, is converted into electrical energy [3].

Modern cities are becoming smarter and smarter. Applications of the Internet of Things (IoT) permit the integration of transport, the optimisation of traffic, the monitoring and control of air pollution, the coordination of emergency actions. Essential to several of the possibilities just mentioned is the deployment of sensors to collect a wide range of data. Besides the cost of purchase, the costs of installation and maintenance (dominated by battery replacement, if this is how sensors are powered) are the main deterrents to an ever denser distribution of sensors around cities.

The use of nano-turbines at the roadside to power road signs, often supplemented with small photovoltaic panels, has become quite common in recent years. Within the built environment of a city, neither energy generator is ideal, either for want of direct sunlight or for safety concerns. An alternative source of energy would be welcome.

Another important factor is of a completely different nature: how do citizens feel about such tight monitoring of their environment? do they see the advantages or do they feel hostility against what could be perceived as a *big brother*?

Newcastle University is currently funding, via Science Central, an ambitious project to monitor the City at multiple scales. As part of the Urban Observatory, a web portal (<http://uoweb1.ncl.ac.uk/>) presents live and stored data including air quality, parking spaces, river levels, etc. The aim of the project summarised in this work was to design and deploy an energy generating device (EGD) capable to supply electrical energy to environmental sensors while engaging the public in a game, to foster public uptake and participation.

### 1.1 EGD's topology and game mechanics

The design of the EGD was governed by two main objectives: efficacy and engagement. It was desired to develop a device capable of generating with a maximum efficacy to make the most of each user's interaction. Large powers were sought, being careful not to demand too much time, as this could reduce future interactions. Naturally, as the most efficient generator would produce no power without input work, the second main objective was to design a game that engaged the public. Several ideas were considered: pedals pushed by stepping on them were discarded due to the difficult installation; bellows that could be used to forge a virtual sword required an overly complex game to support them. Additional considerations included, weather worthiness, public safety, cost and resilience to vandalism.



**Fig. 1.** The Energy Generating Device installed on Newcastle University Campus.

The selected design is based on a handle-driven EGD mounted at shoulder level. The game runs on a mobile phone for quick and easy adoption by the public. As the handle rotates, an LED panel, monitored by the game via the phone's camera, flashes at a frequency proportional to the handle's speed. The game mechanics was designed to encourage the optimal rotational speed of the handle, as dictated by the efficiency of the generator: a clock handle ticks away and can be held back by turning the handle at the correct speed. As time passes, the required accuracy increases until it becomes impossible to achieve it and the game ends.

The EGD was programmed to flash some data – energy produced and battery level – at the end of the game, based on which the user is rewarded. The reward is

proportional to the need of a specific sensor to be recharged. The game displays the battery levels of all sensors available (as this EGD was a unique prototype, this aspect of hunting for the best reward was not applicable).

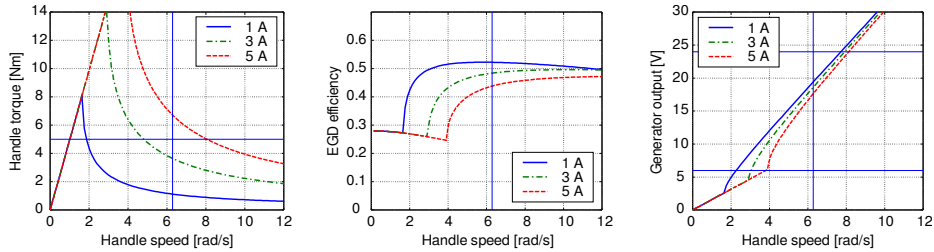
## 2 The Energy Generating Device

Design of the mechatronic system and selection of the components were done with a holistic view, but they are here split in subsections for convenience.

### 2.1 Electromechanical generator

Since it was expected that power would be produced in short but energetic bursts, electromechanical generators were deemed more appropriate than alternatives like piezoelectric transducers, commonly used in EH. From ergonomics data [4] it was found that a comfortable operating condition could be achieved with a crank of radius  $\sim 20$  cm rotated at about 1 turn/second and requiring a force of 15 to 25 N, corresponding to a torque of 3 to 5 Nm and a mechanical power of about 20 to 30 W.

The selection of the generator was quickly narrowed down to the Maxon range of DC and 3-phase AC motors due to the reputability of the manufacturer and the availability of all technical specifications required. The objective was to identify a machine with rated power in the range 20-50 W, appropriate torque and optimal winding. Early considerations showed that the efficiency of the AC range was not significantly superior to DC machines, which were therefore preferred, for the greater simplicity of early power management.



**Fig. 2.** Some performance indicators of the EGD, calculated from eqs. 3 and 4 as a function of handle speed for a selection of required output currents. Some straight lines are added to indicate targeted speed, torque and voltage requirements.

For the selection of wiring and gear ratio, an analytical approach was taken, which is briefly summarised below.

The power balance before and after the Power Management Unit (PMU) is:

$$\eta_{PMU} V_g I_g = V_{out} I_{out} \quad (1)$$

where  $\eta_{PMU}$  indicates the efficiency of the PMU, the  $g$  and  $out$  subscripts refer to quantities *from the generator* and *out of the PMU*, respectively. Considering that the input comes from an electromechanical machine and the output charges the batteries:

$$V_g = k g \omega_h - R_g I_g \quad ; \quad V_{out} = V_b + R_b I_{out} \quad (2)$$

where  $k$  is the electromechanical constant,  $g$  the gear ratio,  $\omega_h$  the angular speed of the handle,  $R_g$  the armature resistance,  $V_b$  the batteries' voltage and  $R_b$  their resistance. Combining (1) and (2), solving for  $I_g$  and selecting the lower branch:

$$I_g(\omega_h) = \frac{k \omega_h g}{2 R_g} - \sqrt{\frac{k^2 \omega_h^2 g^2}{4 R_g^2} - \frac{(V_b + R_b I_{out}) I_{out}}{R_g \eta_{PMU}}} \quad (3)$$

where we indicated that the interest is in the dependence on the handle's speed. The discriminant  $\Delta$  is negative if we attempt to draw more current than is actually available. This means that as long as the demand of  $I_{out}$  cannot be satisfied, it will be limited by the power available (and calculated by setting  $\Delta = 0$ ); in the same regime,  $I_g$  will increase linearly with  $\omega_h$  (this is reflected in the initial linear region in Fig. 2a, since  $\tau_h = k g I_g$ ). Once the limiting power becomes the one at the output (determined by the required  $I_{out}$ ),  $I_g$  must decrease as  $\omega_h$  (and therefore  $V_g$ ) keeps increasing. The plots in Fig. 2 were obtained assuming  $V_b = 3.7$  V and  $R_b = 0.1$   $\Omega$ ; the resulting  $V_{out}$  was always below 4.2 V. The data plotted in Fig. 2 were calculated assuming the PMU had an efficiency of 80%.

The idea was to introduce a control system which regulated the handle's resistive torque  $\tau_h$  via the output current from the PMU, since, assuming a viscous friction in the generator with coefficient  $c$ :

$$\tau_h = g \frac{k I_g + c \omega_h g}{\eta_{gh}} \quad (4)$$

where  $\eta_{gh}$  is the mechanical efficiency of the gearhead.

Expression (3) and others derived from it were plotted in MATLAB with parameters from Maxon's datasheets and expected operating conditions and used to select the optimal generator. Particular attention was devoted to:  $V_g$ , as the PMU, essentially a buck converter, would not switch on below about 6 V; the overall efficiency of the EGD; the torque demanded on the handle. Some examples, for the motor-gearhead selected, are reproduced in Fig. 2. A 36 V motor (Maxon RE 30, P/N 310008) was selected, paired with a 79:1 ceramic planetary gearhead (P/N 166941) that can handle up to 6.0 Nm. Although a 1:1 transmission was deemed suitable, a V-belt was introduced between handle and gearhead-generator to isolate the latter from excessive torques or loads, axial or radial, applied, deliberately or accidentally, to the handle.

## 2.2 Power management and energy storage

The core of the PMU is a DC-DC buck converter based on the LTC3741-1. This was configured for a maximum output voltage of 4.2 V, to satisfy the manufacturer's

recommendation regarding the batteries's charging (two 4.5 Ah Li-Ion batteries of nominal voltage 3.7 V). The output current  $I_{out}$  is set by the voltage applied to a control pin, which was wired to an analogue output of the ATMEGA328P microcontroller.

A 24 V Zener diode (Solid State, 1N3321B) with power dissipation of up to 50 W was connected to the output of the rectifier to limit the voltage to the PMU, whose MOSFETs are rated  $V_{DS} = 30V$ . This means that, if the crank is turned too fast, power in excess of what can be injected in the batteries will be dissipated.

The role of a 15-A full bridge rectifier (Vishay, GSIB1580-E3/45), connected to the output of the generator, is twofold: to permit either direction of rotation of the handle and to prevent the battery from driving the generator as a motor through the body diodes of the switching MOSFETs. A current monitor (Diodes Inc., ZXCT1110W5-7) paired with a 20m $\Omega$  resistor (1% accuracy) sensed the current  $I_g$  entering the PMU; this was used to estimate the input torque ( $\tau_h$ ) and the electrical power into the PMU ( $V_g$  was directly measured).

### 2.3 Controller

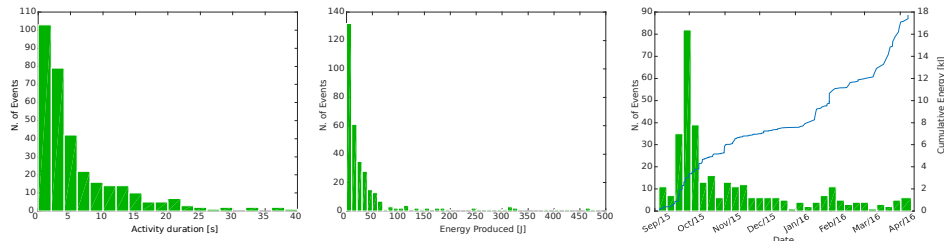
The EGD is controlled by an ATMEGA328P on an Arduino Uno board. This was selected for rapid development, although it is recognised that a host of ancillary components on the board significantly increases the overall power consumption.

The microcontroller is normally off but connected to the PMU. As soon as the handle's rotation generates sufficient voltage to power it up, the microcontroller switches a latching relay to ensure it is constantly supplied from the batteries. It then monitors the input torque, estimated via the generator's current (eq. 4). A PI algorithm adjusts the output current from the PMU to help the user crank at constant speed: if faster, more current/power is demanded, which increases handle resistance, and viceversa if the handle's rotation slows down. The result is a comfortable operation. At every iteration, a tally is updated of the cumulative energy produced in the session. Periodically, data are saved to an SD card in a running log: time; instantaneous voltage and current from generator; handle speed. When the generator voltage drops below a set threshold, the microcontroller enters a waiting state, to determine if the user really intends to stop playing. Once that timeout elapses, the microcontroller disconnects itself and the batteries from the PMU via another latching relay, the batteries voltage is measured and usage data are saved to an SD card in a summary log as well as transmitted to the phone via a sequence of alternate flashes of red and green LEDs. One byte of information is transmitted, twice for redundancy: one nibble contains the battery voltage, the other the energy produced in the session. Finally, the microcontroller reconnects to the PMU and switches itself off by triggering the first relay mentioned.

## 3 Results And Discussion

As Fig. 1 shows, the EGD has been decorated with original characters to appeal to passers-by; a QR code is printed on the front to give a quick way of downloading the

game; 3-step instructions are offered in text format on the side and graphically on the front. The EGD has been installed on a metal post on Newcastle University campus, near the Devonshire building, in September 2015. The device has been removed a year after to assess the condition of the internal components and to download the usage data stored in the SD card. Unfortunately, the weather-proofing was not successful and tens of cubic centimeters of water were found inside. The water did not directly submerge any electronic component, but it created a saturate atmosphere: abundant condensation covered every internal component. Despite rust and oxidation, the EGD was still perfectly operational once new batteries were connected, but the original ones had suffered serious damage and, once generation had stopped, were unable to keep supplying neither the micro-controller nor the real time clock (RTC). For this reason, the last time-stamped entry found on the SD card is dated 2016-04-10; subsequent entries were all time-stamped 2000-01-01, indicating the RTC had reset. The summary logs are absent after that date, since they are saved on battery power.



**Fig. 3.** Histogram plots indicating the number of interactions from users binned with respect to their duration (left) and the energy produced (right). Five more events lasted more than 40s and another five produced more than 500 J each.

Focusing on the first 7 months, when complete and reliable data is available, about 330 distinct interactions have taken place. As Fig. 3 shows, they were most often very brief events in which very little energy was produced (80% below 50 J). It is possible to imagine that in these cases the users turned the handle once or twice, just to see what happened. Regarding the time distribution, higher interest is observed at the beginning, coinciding with the beginning of the term (first week of October). The cumulative energy output by the DC generator is also reported on the last graph in Fig. 3 and shows how the numerous events observed in September/October 2015 have been very low energy ones. A total of 18 kJ were generated in the 2400 s of activity, with an average power (while active) of 7.4 W and an overall average power of 1 mW. A further 200 events were recorded between April 2016 (when the RTC reset) and the beginning of September 2016, when the EGD was removed, but reliable data on total energy produced is not available for them.

Regarding the game, issues with the server and with camera-compatibility prevented the collection of usage data, although we do know that the game was downloaded 16 times, including by people associated with the project. It is estimated that about a dozen genuine users have used the game and registered an account.

## 4 Conclusions

A hand-powered electromechanical generator has been designed, built and installed on campus for 12 months. The device worked as designed during lab testing, however insufficient weather-proofing caused anomalies 7 months after installation due to water infiltration.

The large number of interactions recorded suggests that the device was successful in attracting the attention of passers-by, although most of these appear to be just occasional users who produced little energy. When this level of interest is contrasted with the very low number of game downloads, we deduce that the targeted public (mostly university students) is reluctant to engage in this way. It is suggested that focus is given to some form of immediate “action” happening on the EGD itself, to satisfy the initial curiosity of the occasional users and keep them engaged. The lack of sustained interest from the public translated into overall poor power generation. A sheltered location would be beneficial not only to the EGD itself but also for public interaction, in particular if it was, rather than a transit area, a place where people stop to rest or socialise.

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